DTRA MHD-E3 Phase IVB

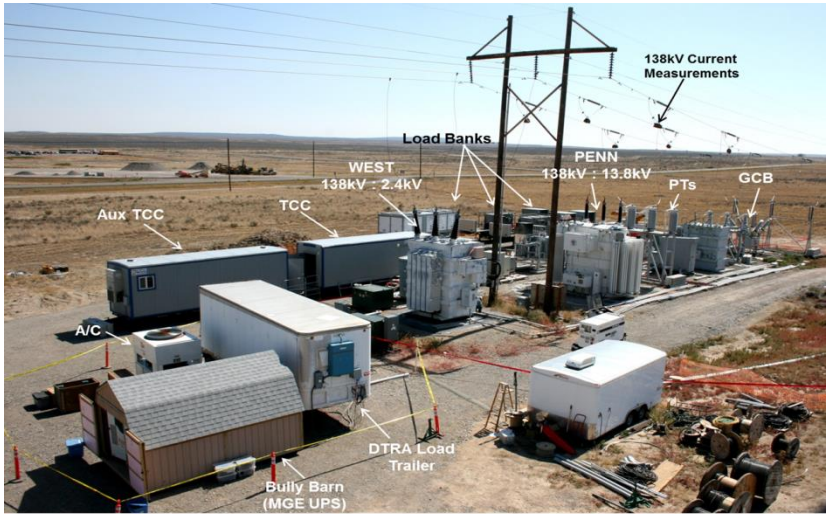
Measured Harmonic Response of Power Grid Transformers Subjected to Severe E3/GIC Currents

August 2013

Michael Rooney, DTRA
Dave Fromme, SARA
Greg Edmiston, SARA
Amber Walker, SARA
Shawn West, INL
Scott McBride, INL

Outline

- Background / Objectives / Brief Introduction to the Testbed
- Neutral Current Time Development
- Harmonics Results
  - Transformer Primary Side Response
  - Transformer Secondary Side Response
- Operational Results/Summary

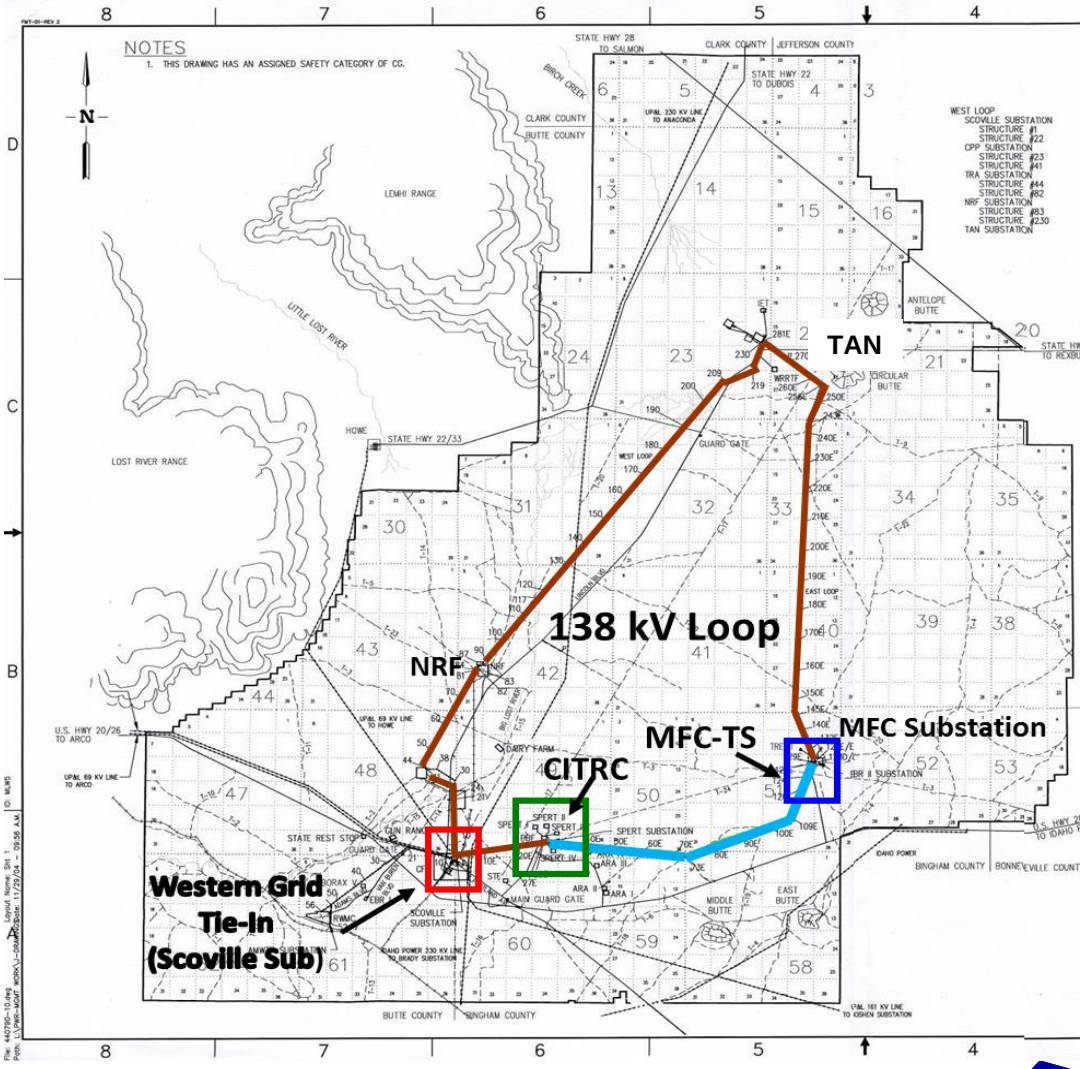


Objectives

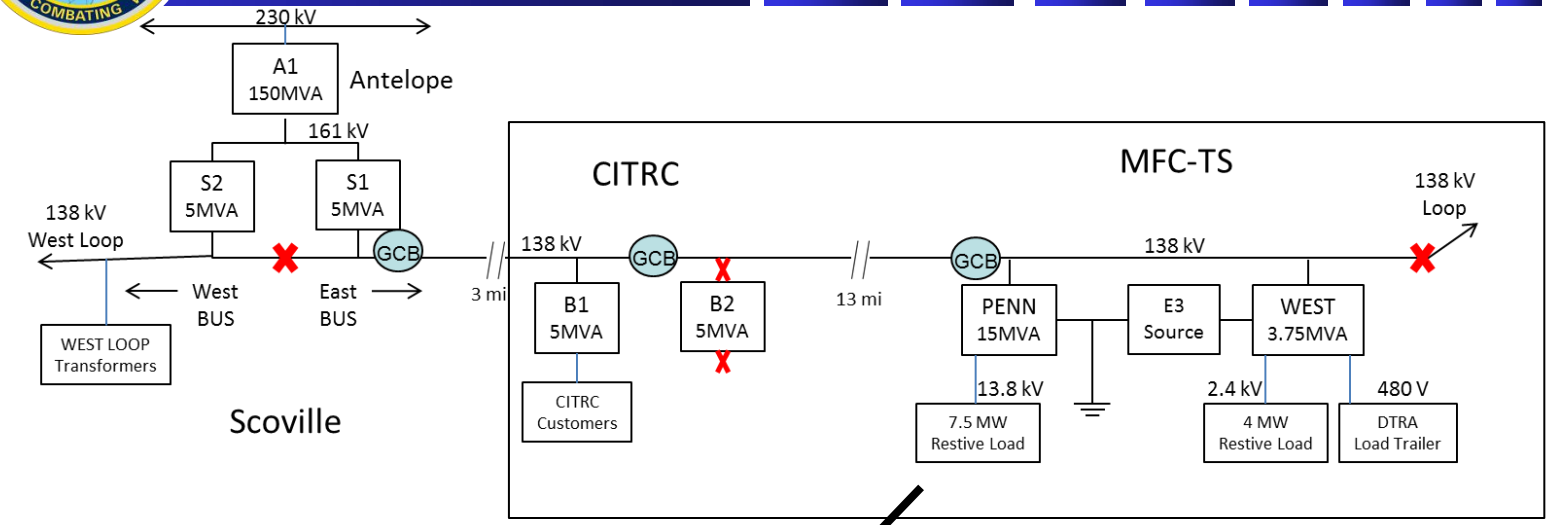
- Eliminate major limitations in 2011 tests
  - CITRC stepup-stepdown (source impedance) limitation
    - > Data suggests that this limitation affected both the surge current into MFC and the “stiffness” of the MFC-TS 138 kV high-side voltage
  - Increase Loading – from ~10% in 2011 to 50/100% in 2012
  - Compare protective relay response changes due to source impedance change
  - Add diagnostics on sound/vibration and internal temperature

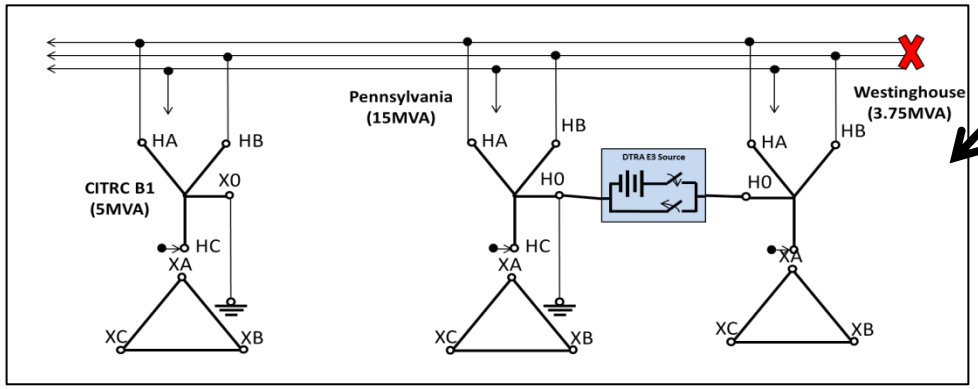
Test Layout-Idaho National Laboratory

- INL 138 kV Loop
  - Materials and Fuels Complex-Test Site (MFC-TS)
    - > Test Control Center
    - > DTRA Source
    - > Loads
  - Critical Infrastructure Test Range Complex (CITRC) Substation
    - > INL Grid Control Station
    - > Additional Measurements
  - Scoville Substation
    - > Western Power Grid Feed
    - > Additional Measurements



Block Diagrams Configurations





Loading Name	Code	Load Type	PENN Loading	WEST Loading	Tests
Baseline Repeat	BHR	Resistive	1.5 MW 10%	375 kW 10%	29
Baseline Extended	BHE	Resistive	7.5 MW 50%	2 MW 50%	12
Complex Repeat	L5R	Resistive & Complex	1.5 MW 10%	375 kW 10%	11
Complex Extended	L5E	Resistive & Complex	7.5 MW 50%	2 MW 50%	14
Complex Full	L5F	Resistive & Complex	7.5 MW 50%	3.75 MW 100%	5
Complex No HEMP Filter	L5RN/L5EN	Resistive & Complex	10%-50%	10%-50%	6
Emprimus Global	L5R/L5E/L5F	Resistive & Complex	10%-50%	10%-100%	16
Emprimus Local	L5RL	Resistive & Complex	1.5 MW 10%	375 kW 10%	11

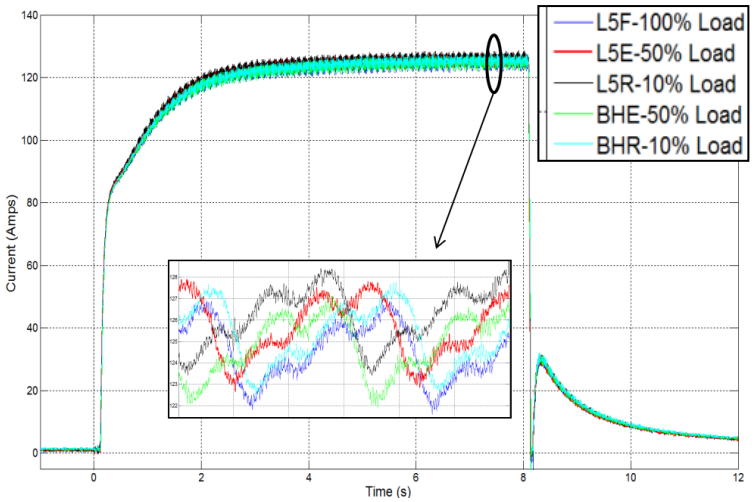
104 Simulated events
2 Old 3.75 and 15 MVA 138 kV transformers
Complex loads at 10-50/100% rated loading

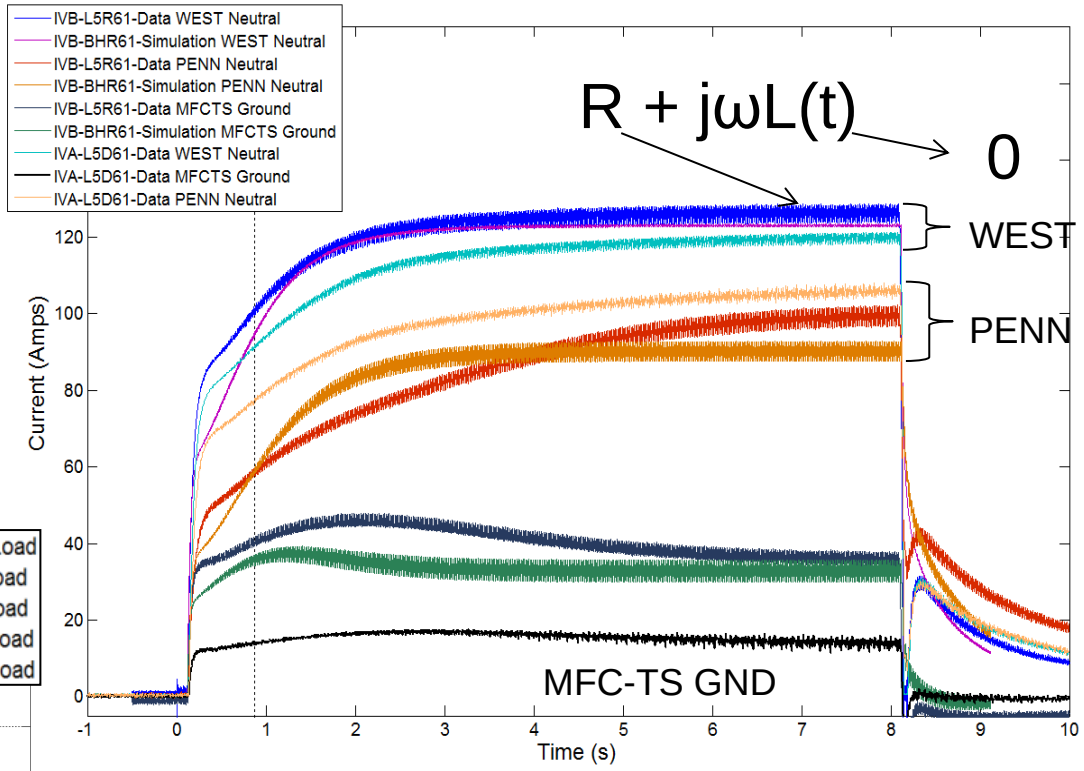
Outline

- Background / Objectives / Brief Introduction to the Testbed
- Neutral Current Time Development
- Harmonics Results
  - Transformer Primary Side Response
  - Transformer Secondary Side Response
- Operational Results/Summary

IVB/IVA DC Current Split
(L5R(2012)/L5H(2011) @ 61 batteries)

- 120 A Injection in to WEST Neutral
- Loads do not affect DC current
- IVA
  - Splits different (No world transformers)
- IVB
  - Model missed initial current breakpoint
  - Model predicted split at 2.5:1 to < 5%
  - Model missed imbalance substantially





Outline

- Background / Objectives / Brief Introduction to the Testbed
- Neutral Current Time Development
- Harmonics Results
  - Transformer Primary Side Response
  - Transformer Secondary Side Response
- Operational Results/Summary

IEEE 519-1992

The limits listed in Table 11.1 should be used as system design values for the "worst case" for normal operation (conditions lasting longer than one hour). For shorter periods, during start-ups or unusual conditions, the limits may be exceeded by 50%.

Table 11.1
Voltage Distortion Limits

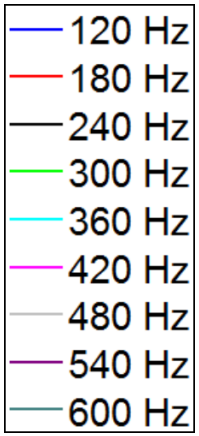
Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

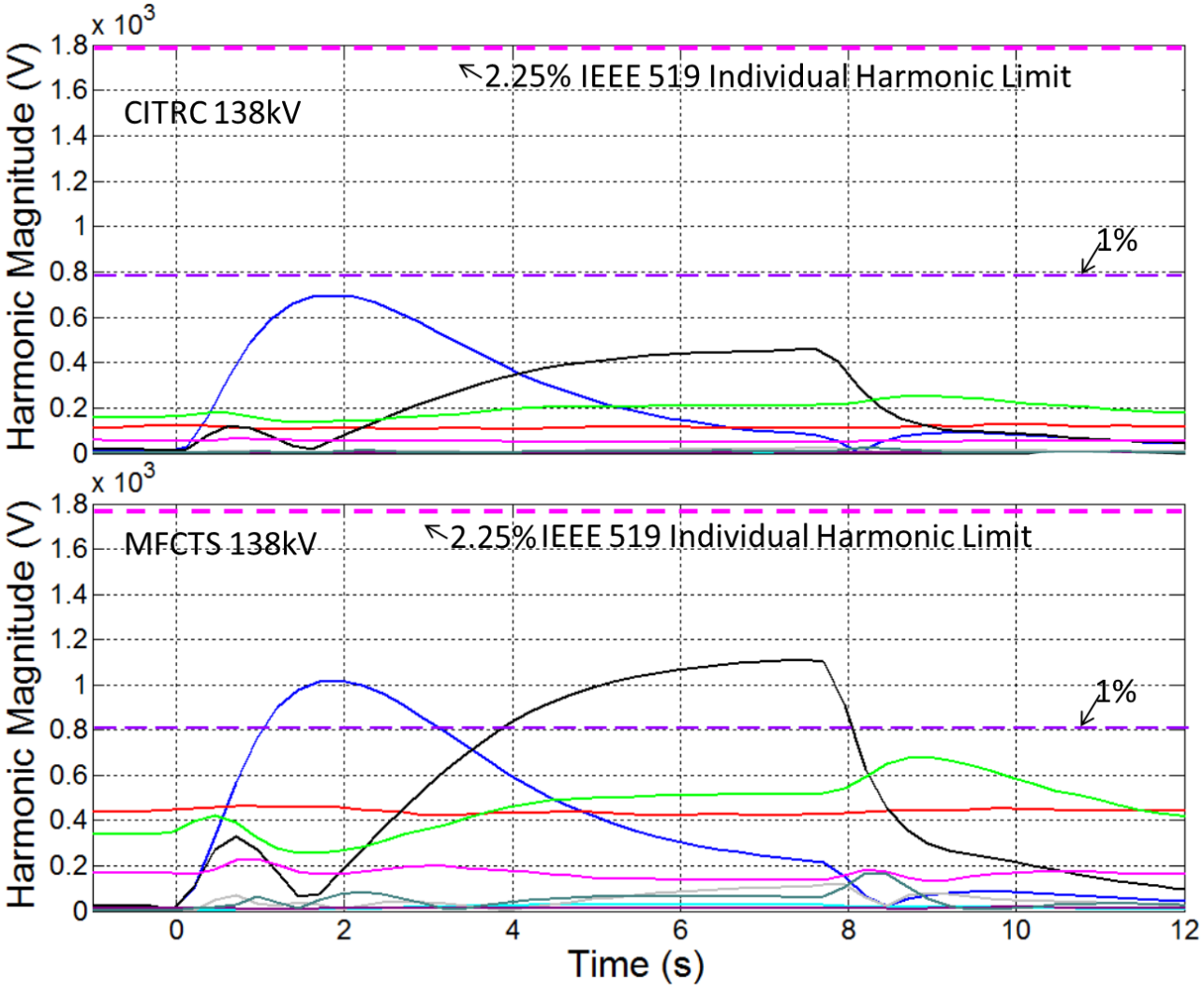
NOTE: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

- High Voltage (138kV) Short Period Limits
  - Individual Harmonics = 2.25%
  - Voltage Total Harmonic Distortion = 3.75%
- Medium/Low Voltage Short Period Limits
  - Individual Harmonics = 4.5%
  - Voltage Total Harmonic Distortion = 7.5%

IVB 138kV Individual Harmonics

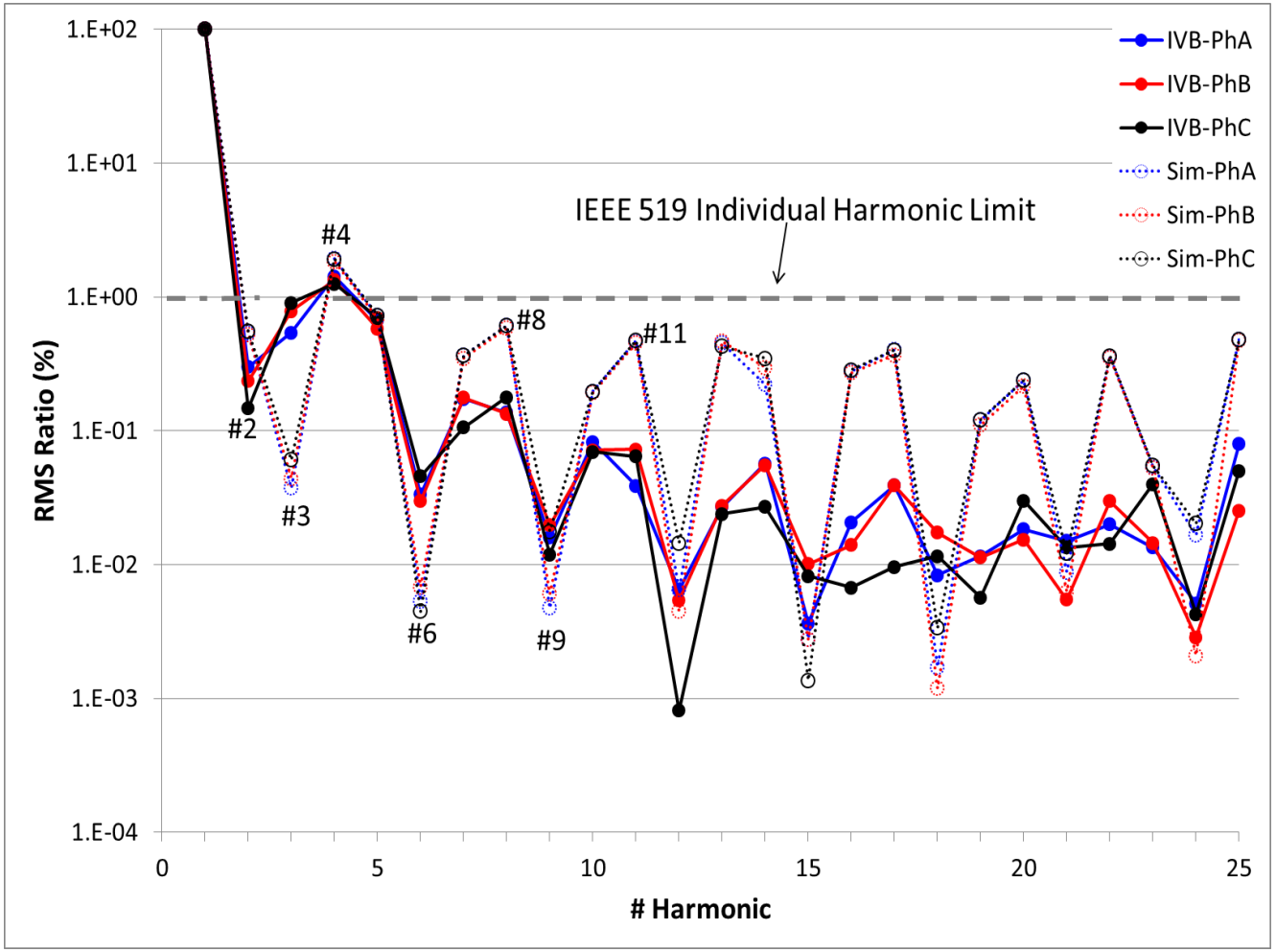
- Time history differs for harmonics
- $2^{nd}/4^{th}$ dominating harmonics
- Larger at MFC-TS





V138kV Harmonics (Sim v Data) towards end of E3 pulse

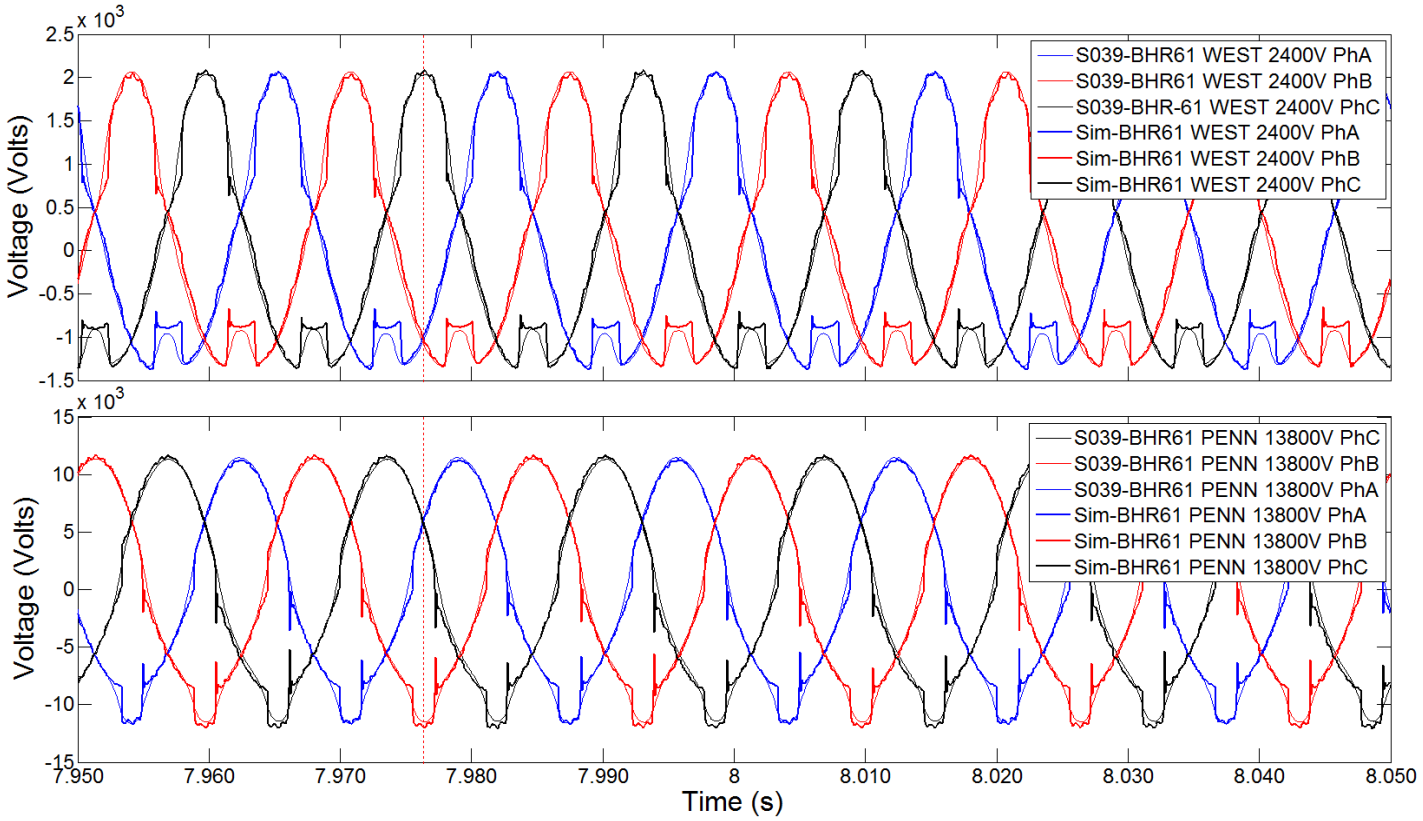
- Simulation overpredicts higher order harmonics
  - See “sharpness” of surge currents
  - Also manifests on secondary side



Outline

- Background / Objectives / Brief Introduction to the Testbed
- Neutral Current Time Development
- Harmonics Results
  - Transformer Primary Side Response
  - Transformer Secondary Side Response
- Operational Results/Summary

Secondary Voltages (Sim vs. Data)

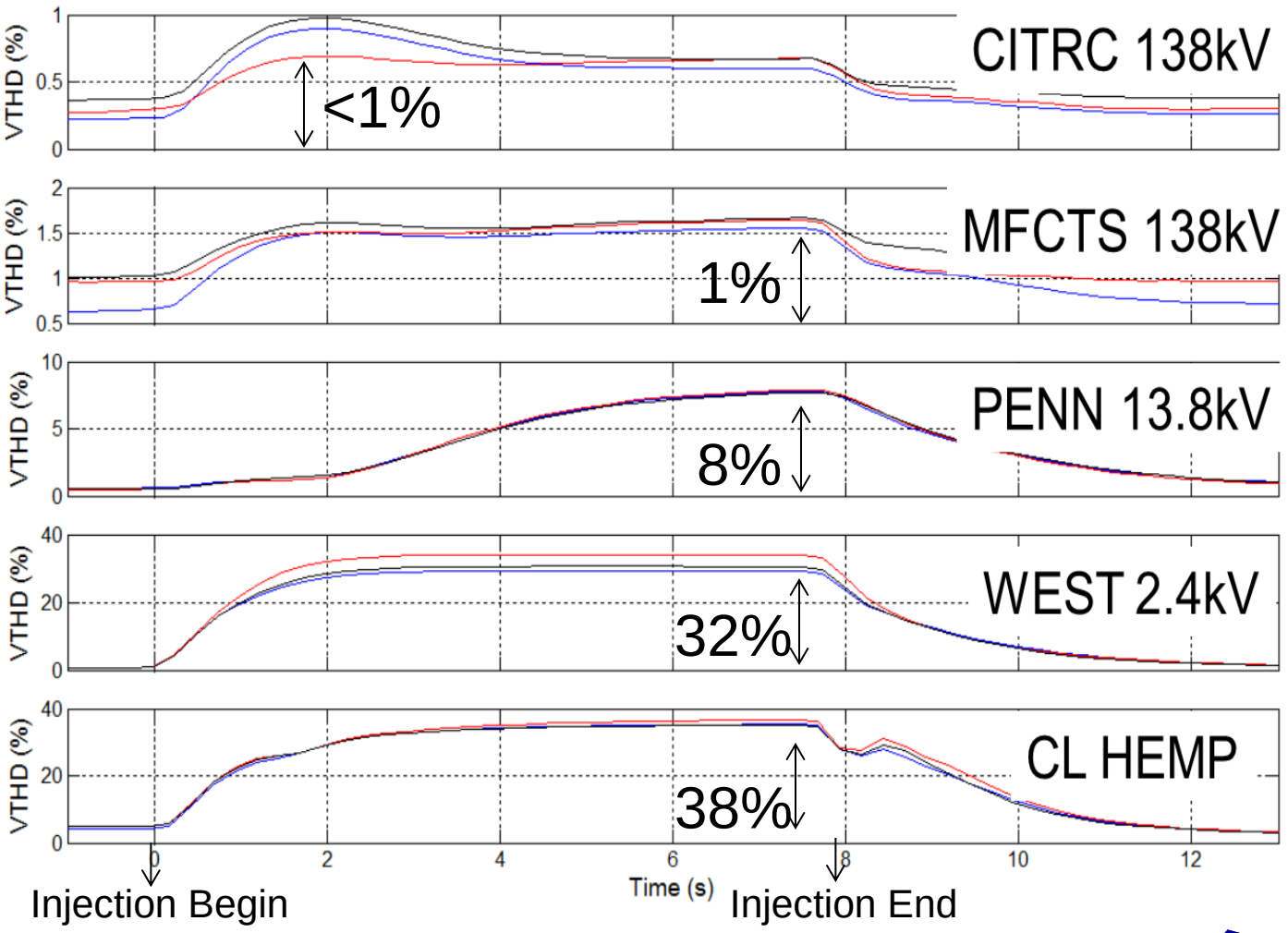


- The sharp edges on the negative (non-saturating) half cycle are responsible for the overprediction of the higher order harmonics.

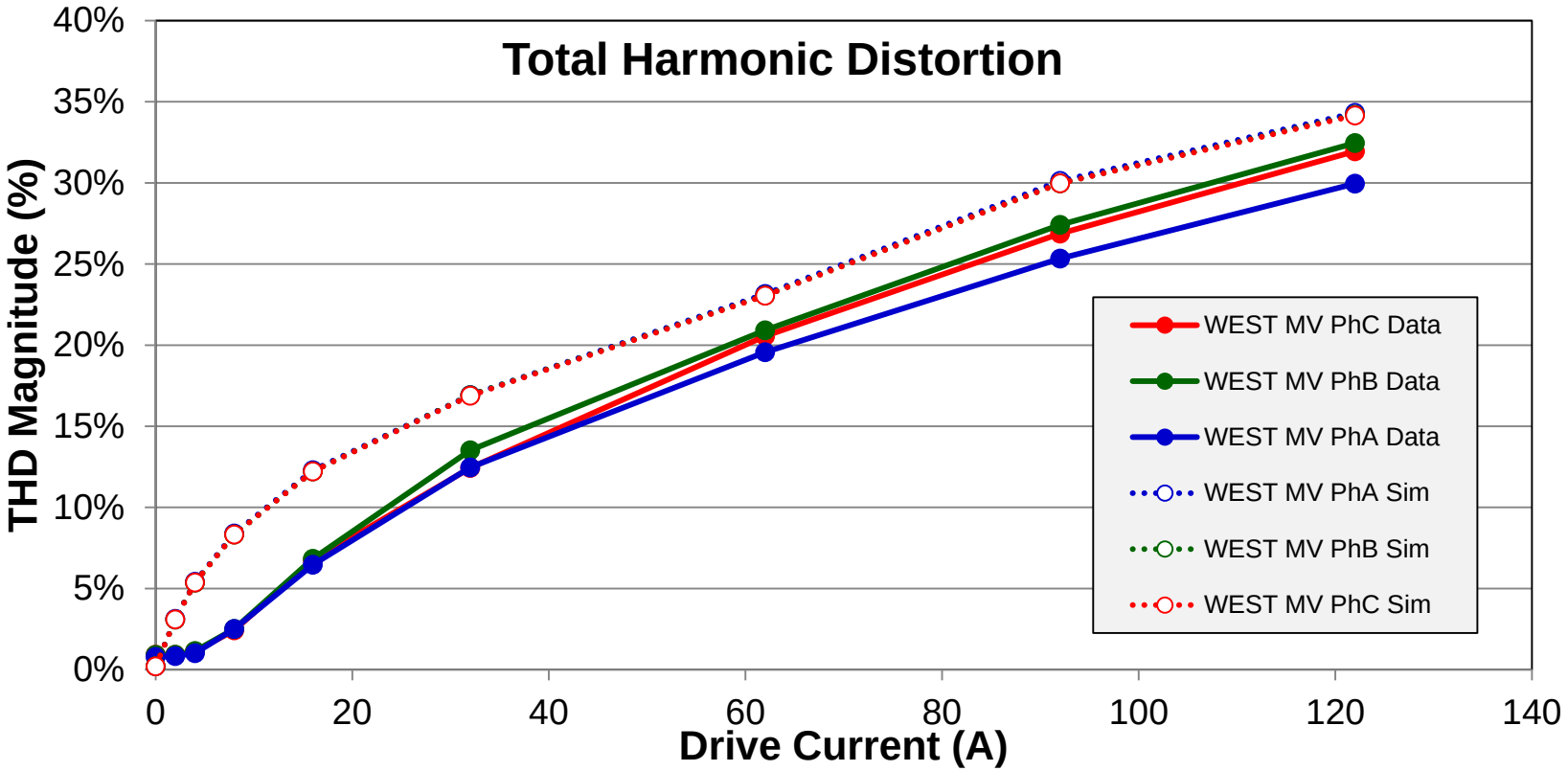
Voltage Total Harmonic Distortion

- Voltage total harmonic distortion across test grid
- L5E-50% Complex Loading Configuration
- Time development of V_{THD} varies
- V_{THD} dominated by grid source (S_1) and saturating transformers

(see next slide)

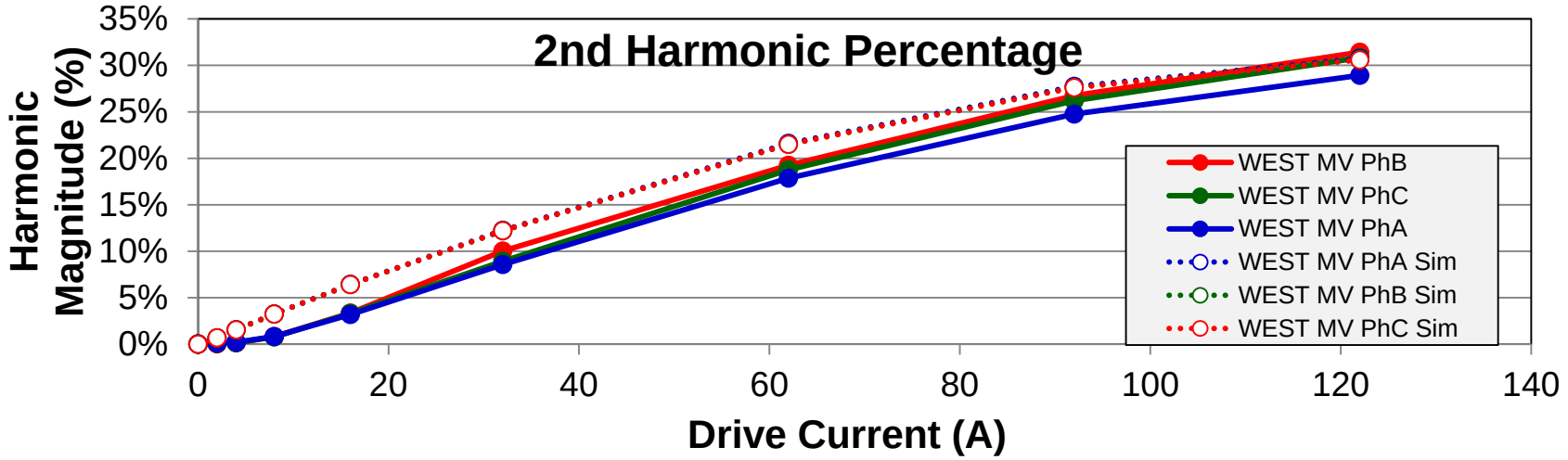


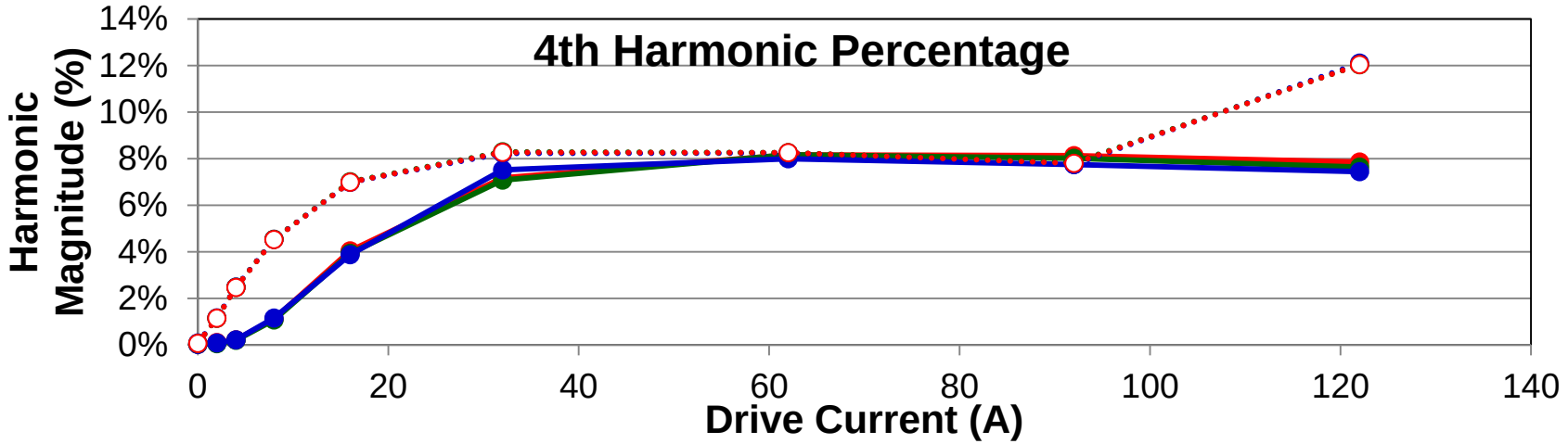
Secondary Harmonic Trends



- Max THD of ~33%
- Model predictions within 2x throughout
  - Better at higher drive

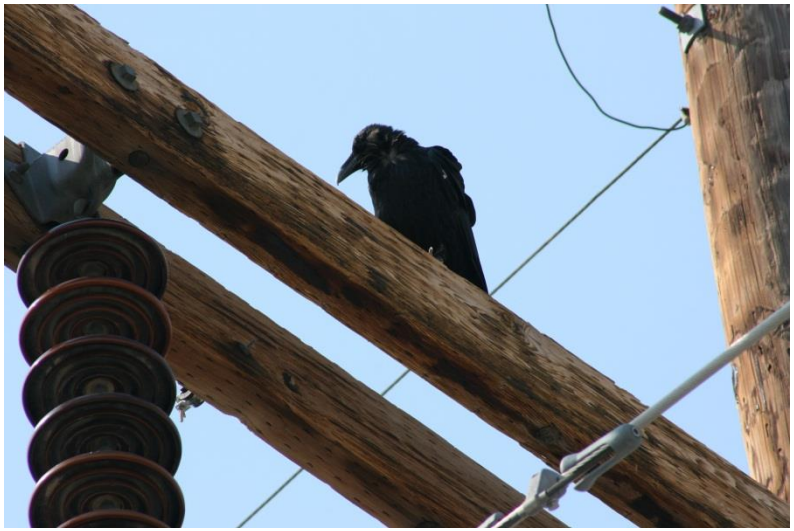
Sample Individual Harmonics





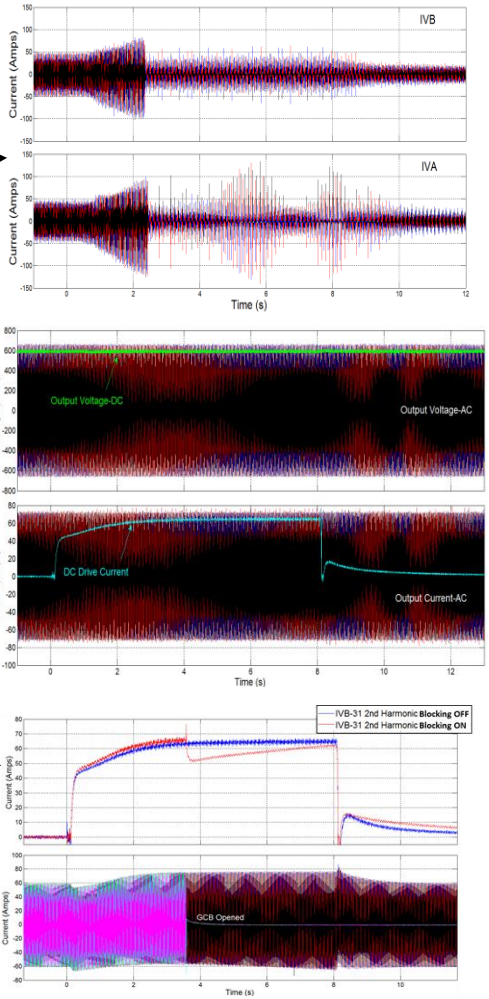
Outline

- Background / Objectives / Brief Introduction to the Testbed
- Neutral Current Time Development
- Harmonics Results
  - Transformer Primary Side Response
  - Transformer Secondary Side Response
- Operational Results/Summary



Operational Results-A/C Thermal Trip

- Transformer
  - Loud Hum
  - No detectable oil temperature change – No Hot spot diagnostic
- 30 Ton Air Conditioner Unit
  - Experienced a Thermal trip during IVA and IVB for > 30 Amps
  - Manual reset required for all thermal trips
- MGE, Chloride, Eaton UPS's Tested
- Two Samples of VFD's Tested
  - No UPS outages (battery replacement in 2012)
  - One possible VFD reset
- No Protective Relay Activations
  - Normal Settings - 2nd Harmonic Blocking
  - 2nd Harmonic Blocking Off Tripped – As expected
  - SEL can detect but cannot distinguish In-rush / GIC/HEMP



Overall Summary

- All test objectives were achieved
  - Removing the isolation at CITRC created a stiffer source
  - Increased loading from 10% in IVA to 50/100% in IVB
  - Grid Source and saturating transformers empirically proven to be dominating factors, not loading levels or types
    - > Harmonics measured and modeled
  - Operational Responses
    - > Protective relays were adjusted and possible unique identifiers investigated
    - > Heating and Local Voltage Stresses – Diagnostics Introduced
- Model results relatively good with generic parameters
- Limitations
  - No saturating auto transformers
  - SVAR compensators not included
  - Transformers tested at 10s of MVA – common is 50-500 MVA